



Towards a continental-scale biodiversity monitoring network to assess climate-driven change in bat communities and inform European Union conservation policy

Francesco Belluardo^{a,b,c,*}, Federica Roscioni^{b,c,**}, Adrià López-Baucells^d, Danilo Russo^e, Luca Santini^f, Penelope C. Fialas^g, Hugo Rebelo^{h,i}, Orly Razgour^g, Francisco Amorim^{j,k}

^a ZooMod Lab, Department of Biosciences and Territory, University of Molise, Contrada Fonte Lappone s.n.c., 86090, Pesche, Italy

^b Ecomodel Società Cooperativa, Via Tiberina, 149, 00188, Roma, Italy

^c Biodiversity Monitoring and Conservation Enterprise (Biome), Department of Biosciences and Territory, University of Molise, Contrada Fonte Lappone s.n.c., 86090, Pesche, Italy

^d BiBio Research Group, Natural Sciences Museum of Granollers, Av. Francesc Macià, 51, 08402, Granollers, Spain

^e Laboratory of Animal Ecology and Evolution (AnEcoEvo), Department of Agricultural Sciences, University of Naples Federico II, Piazza Carlo di Borbone, 1, 80055, Portici, Italy

^f Department of Biology and Biotechnologies 'Charles Darwin', Sapienza University of Rome, Piazzale Aldo Moro, 5, 00185, Roma, Italy

^g Biosciences, University of Exeter, Stocker Road, EX4 4QD, Exeter, United Kingdom

^h Centre for Ecology, Evolution and Environmental Changes (CE3C), Faculdade de Ciências, Universidade de Lisboa, Campo Grande, 1749-016, Lisboa, Portugal

ⁱ Global Change and Sustainability Institute, Departamento de Biologia Animal, Faculdade de Ciências, Universidade de Lisboa, Campo Grande, 1749-016, Lisboa, Portugal

^j CIBIO, Centro de Investigação em Biodiversidade e Recursos Genéticos, InBIO Laboratório Associado, Universidade do Porto, Campus de Vairão, Rua Padre Armando Quintas, 7, 4485-661, Vairão, Portugal

^k BIOPOLIS Program in Genomics, Biodiversity and Land Planning, CIBIO, Campus de Vairão, Rua Padre Armando Quintas, 7, 4485-661, Vairão, Portugal

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ABSTRACT

As impacts of climate change on biodiversity are increasing globally, decision-makers urgently need scientifically robust, long-term monitoring data on biodiversity responses to inform effective conservation strategies. We designed a European-scale monitoring network to assess climate change effects on bat communities, integrating species distribution models under current and future climatic scenarios with spatial conservation planning tools to identify suitable monitoring sites across the continent. The monitoring design followed a hypothesis-driven framework, defining projected species range shifts and community turnover as measurable indicators within the Essential Biodiversity Variables framework, and applying a standardized and spatially optimized approach to assess climate-driven changes. The optimized site selection also incorporated practical implementation aspects, including workforce availability and variable levels of monitoring efforts. We applied this framework to a regional case study from Catalonia (Spain) that illustrates how existing national or subnational programs not originally designed for climate research can be adapted to detect climate impacts on regional bat communities, thereby providing a foundation for a future European-scale network built upon ongoing monitoring initiatives. The proposed continental network can support the European Union in addressing commitments on biodiversity conservation and climate policy, while providing information relevant to Member States reporting obligations and implementation of key policy instruments such as the Habitats Directive, Biodiversity Strategy for 2030, and Nature Restoration Regulation. The proposed framework offers substantial flexibility and scalability across both spatial and taxonomic dimensions and, although developed for bats, is broadly transferable across geographic regions and taxonomic groups, providing a generalizable approach for climate-informed biodiversity monitoring.

* Correspondence to: F. Belluardo, Contrada Fonte Lappone s.n.c., 86090, Pesche, Italy.

** Correspondence to: F. Roscioni, Via Tiberina, 149, 00188, Roma, Italy.

E-mail addresses: francesco.belluardo@unimol.it (F. Belluardo), federica.roscioni@ecomodel.eu (F. Roscioni).

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1. Introduction

Climate change has emerged as a major threat to biodiversity, and although its effects are often framed primarily as future risks, many species have already experienced population declines and local extirpations and, in some cases, extinctions (Jaureguiberry et al., 2022; Maxwell et al., 2019; Waller et al., 2017). The effects of climate change are projected to intensify in the future at a pace exceeding those of other anthropogenic pressures (IPCC, 2022; Jaureguiberry et al., 2022; Newbold, 2018). Many species are already responding to changing climatic conditions, with distributional shifts to track suitable habitats within their climatic niches among the most frequently reported responses (Bellard et al., 2012; Chen et al., 2011; Festa et al., 2023).

The urgent need to mitigate climate change impacts on biodiversity is recognized in international policy frameworks, most recently through the Kunming-Montreal Global Biodiversity Framework under the Convention on Biological Diversity (CBD; CBD, 2022). However, to support effective conservation strategies, decision-makers require robust scientific evidence on climate change effects, underscoring the critical importance of monitoring biodiversity change (CBD, 2022; Dalton et al., 2023; Gonzalez et al., 2023).

Regardless of the biodiversity level assessed (i.e., genes, populations, species, communities, ecosystems), the effectiveness of monitoring programs ultimately depends on clearly defined monitoring questions, appropriate targets, and measurable indicators (Dalton et al., 2023; Gonzalez et al., 2023; Legg and Nagy, 2006; Lindenmayer and Likens, 2009). In this regard, the Essential Biodiversity Variables (EBVs) framework provides a standardized basis for biodiversity monitoring and is highly relevant for policy and decision-making, as it identifies measurable and scalable variables related to key species and ecosystem attributes which are linked to CBD targets and indicators (Dalton et al., 2023; Pereira et al., 2013).

Among the EBVs, species distribution is particularly important because distributional shifts can be feasibly detected and measured through the recording of species presence/absence, and occurrence records can be readily integrated across diverse sources (e.g., museum records, citizen science, atlases, field surveys) (Jetz et al., 2019; Pereira et al., 2013). As such, changes in species distribution are considered among the most policy-relevant biodiversity responses to climate change (Jetz et al., 2019). However, many monitoring programs addressing potential species range shifts are rarely informed by future climate change scenarios when selecting monitoring sites, which means that areas most likely to experience range shifts are often undersampled (Amorim et al., 2014; Carvalho et al., 2016; Jetz et al., 2019). Given the accelerating pace of climate change (IPCC, 2022; Jaureguiberry et al., 2022; Newbold, 2018), it is essential to design monitoring networks that explicitly target predicted distributional changes, ensuring they remain informative for conservation strategies over the coming decades and enabling hypothesis-driven assessments of climate change impacts. The incorporation of predicted species range shifts, based on climate change projections, has been proposed as a methodological framework (Amorim et al., 2014; Carvalho et al., 2016; Higa et al., 2013), but has rarely been implemented in the design of monitoring networks.

Bats represent an excellent model for studying climate impacts due to several distinctive aspects of their biology and natural history that make them particularly sensitive (Festa et al., 2023): they are facultative heterotherms and thus strongly dependent on temperature variation (Stawski et al., 2014); their relatively high surface-area-to-volume ratio makes them especially sensitive to dehydration (Korine et al., 2016); many are migratory, with specific phenological patterns that can be disrupted by changing climatic conditions (Rydell et al., 2014); and their slow K-selected reproductive strategies make population responses particularly limited under rapid climatic change (Famoso et al., 2018). At the same time, their strong dispersal abilities enable bats to potentially track climate change by shifting to suitable habitats more effectively than most non-flying vertebrates (Festa et al., 2023). Indeed, some

of the most frequently reported or predicted effects of climate change on bats are distributional range shifts and upslope movements to higher elevations (Festa et al., 2023; Russo et al., 2024a; Russo et al., 2024b). Recently, Fialas et al. (2025) predicted that bats in Europe will undergo substantial shifts in geographic range resulting in changes in their functional trait space, with possible consequences for ecosystem services. Changes in migratory phenology have also been documented, in some cases consisting of sex-based mismatches that can reduce reproductive success (Dondini et al., 2025; Festa et al., 2023). Furthermore, mass mortality events or unusually high mortality rates have been associated with extreme climatic events (e.g. droughts, wildfires, heat-waves, extreme cold), the frequency of which is expected to increase under climate change (Festa et al., 2023; Flaquer et al., 2014; McSweeney and Brooks, 2022; Russo et al., 2025).

Despite these examples, a comprehensive understanding of ongoing climate change impacts on bats is still lacking, as empirical evidence remains sparse and heterogeneous in terms of methodological approaches and taxonomic and geographic sampling (Festa et al., 2023). There is a critical need for long-term, field-based observational studies, since short-term investigations may only capture responses to processes such as interannual weather fluctuations rather than to long-term climatic trends (Festa et al., 2023).

In addition, in the European context, all bat species are of high conservation value, being listed under the Habitats Directive (Council Directive 92/43/EEC; EC, 1992), and bat conservation is further supported by the Agreement on the Conservation of Populations of European Bats (UNEP/EUROBATS, 1991), which fosters coordinated transnational monitoring and conservation actions. This legal status requires strict protection measures and obliges the European Union (EU)'s Member States to regularly report on their conservation status within the context of the general Union's biodiversity policy framework. These aspects underscore the urgent need to design and implement a coordinated, long-term monitoring program at the continental scale, which should not overlook or replace existing national and regional efforts, but instead integrate ongoing monitoring programs, many of which already generate valuable data and insights (Santana et al., 2025). We therefore propose a European-scale network to monitor the effects of climate change on bats, developed within the framework of the European Cooperation in Science and Technology (COST) Action CA18107 'Climate change and bats: from science to conservation – ClimBats'. Specifically, in this study we aim to:

- (1) Design a European-scale monitoring network by identifying suitable monitoring site locations to detect bat distributional shifts under future climatic scenarios, integrating species distribution models (SDMs) with optimization algorithms for spatial conservation planning (SCP) and complemented by practical guidelines for the effective implementation of long-term monitoring activities. This will provide an evidence-based and scientifically rigorous framework supporting EU's biodiversity policy and international commitments.
- (2) Present a regional case study for Catalonia (Spain) to demonstrate how existing monitoring networks not originally designed for climate change can be integrated and adapted for a climate-driven focus, providing a model for other European regions.

2. Methods

2.1. Analytical framework

We implemented the methodological framework presented in Fig. 1 and Fig. S1 to design a monitoring network to detect species range shifts under climate change through the application of a SCP approach based on a decision support tool (Marxan software; Ball et al., 2009) to select the optimal location of monitoring sites. Briefly, areas within Europe where bat species are expected to show stronger responses to future

scenarios of climate change were used as input layers, derived from SDMs and community turnover of bats obtained from Fialas et al. (2025). The optimization process considered where such areas occur while minimizing the costs associated with accessibility to the areas and low habitat quality for the species, while prioritizing Natura 2000 sites and Protected Areas (PAs). We applied this analytical framework to design a monitoring network at the continental European level (including Turkey) and at a regional scale (Catalonia, Spain). A detailed description of each analytical step is provided in the following sections.

2.2. Data retrieving and processing

2.2.1. Planning units

Marxan uses ‘planning units’ as the baseline for the optimization process and solves an objective function to find sets of planning units that meet representation targets for conservation features while minimizing costs (more details in the following sections). In the present study, planning units consisted in a regular grid of 10×10 km squared cells corresponding to the reference grid of the European Environment Agency (EEA; <https://www.eea.europa.eu/>; Fig. S1). Planning units selected in Marxan best solution represent the network of monitoring locations. In this framework, such locations should be interpreted as priority areas for monitoring implementation rather than as predefined point locations where monitoring data are collected, whose exact configuration will depend on the monitoring protocols ultimately adopted (see Supplementary Text for details). For simplicity, throughout the manuscript, the terms ‘monitoring station’, ‘site’, and ‘location’ are used at the network-design stage to refer to selected planning units, rather than to specific field-sampling locations.

2.2.2. Conservation features

2.2.2.1. Species distributional range shifts and stable areas. We retrieved SDMs of 37 European bat species from Fialas et al. (2025) to determine potential present-day distributions and expected potential distribution under future climate change scenarios based on modeled species-specific habitat suitability (see Supplementary Text for a summary of SDM development and assumptions). We subtracted present-day SDMs from future SDMs to determine potential distributional changes, specifically areas where species are predicted to expand their ranges (range gain), contract their ranges (range loss) or preserve their present-day ranges (range maintenance). Range maintenance areas were included as they act as climatically stable control regions, providing baselines against which data collected from areas of expected range gain or loss can be compared to evaluate climate change effects against non-climatic background variability in bat responses. These three categories of areas represent the conservation features of Marxan analyses (see 2.3.1.1 Conservation features and climate change velocity).

Given the impracticality of monitoring all European bat species, we focused on taxa expected to be the most climate-sensitive and easily monitorable using bioacoustics among European species (see Supplementary Text and Table S1 for details on species selection). We selected 11 different species, which relative to the three range-change categories (gain, loss and maintenance) represent 17 conservation features (combination of species and range change category) (Table S1), which were further divided by each European country, resulting in 569 conservation features. A summary of data processing and Marxan input preparation is provided in Fig. S1. All data processing described in this and the following sections was performed in QGIS 3.22.11 and R 4.2.3 (QGIS Development Team, 2023; R Core Team, 2026).

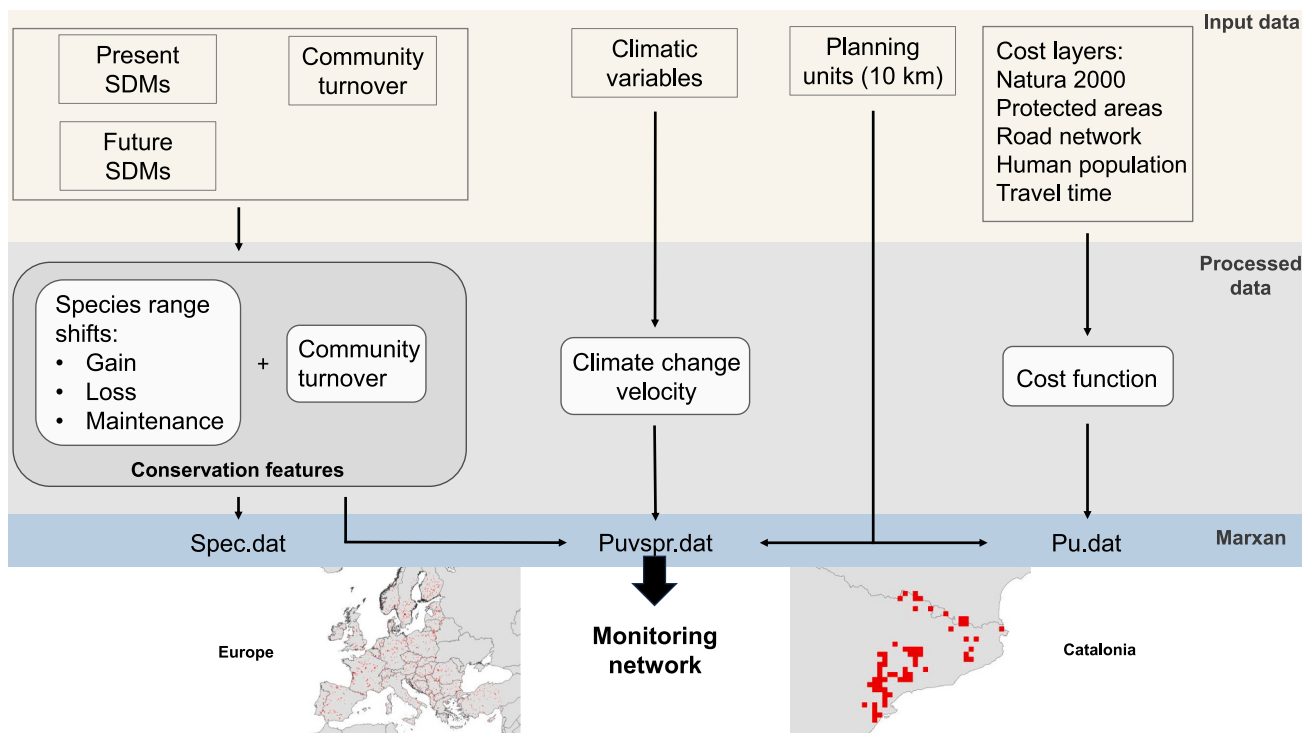


Fig. 1. Conceptual workflow of the analytical framework used to design the European and Catalonia's bat monitoring networks. Input data (top) include present and future species distribution models (SDMs) and SDM-derived community turnover (both retrieved from Fialas et al., 2025), climatic variables, planning units (10-km grid cells), and spatial cost layers (see Table S2). These inputs were processed to derive conservation features, including projected species range shifts (gain, loss, and maintenance) and community turnover divided by each European country, as well as additional metrics such as climate change velocity and a composite cost function. Conservation features, climate change velocity, and costs were translated into Marxan input files (spec.dat, puvspr.dat, and pu.dat), which were used to optimize the spatial configuration of monitoring sites. The resulting optimized monitoring network was produced at both continental (Europe) and regional (Catalonia, Spain) scales.

2.2.2.2. Community turnover and climate change velocity. The community turnover layer from Fialas et al. (2025) was incorporated into Marxan analyses as an additional conservation feature and divided by each county for a total of 37 conservation features (Fig. S1; see **Supplementary Text** for a detailed description of the layer). A climate change velocity layer was also included to prioritize monitoring stations in regions where climatic conditions are projected to change most rapidly (Fig. S1; see **Supplementary Text** for details on climate change velocity calculations).

2.2.3. Cost function and initial reserve system-locking layers

We used layers of Nature 2000 and PA networks to set the Marxan cost function and layers of human population, road network and travel time from urban centers to define areas to lock out from the initial reserve system (Fig. S1; Table S2).

We included Nature 2000 sites and PAs and prioritized them in the cost function for different reasons. Firstly, for Member States reporting obligations under Habitat Directive (EC, 1992). In addition, habitats within protected networks should presumably be more pristine and species-rich (including ecologically specialist species) than nearby areas lacking legal protection, therefore, climate change effects on bat communities should be more feasibly disentangled from other biodiversity threats, making monitoring data collected within Natura 2000 sites and PAs on species distributions and compositions more informative for the monitoring network objectives. Finally, biologists and park rangers working within Natura 2000 sites and PAs could represent an invaluable workforce for monitoring activities. Information on Natura 2000 and PA networks was incorporated in the analyses by computing the proportion occupied by the sum of the areas of Natura 2000 sites and PAs within each planning unit.

Human population and road network layers were used to lock out from Marxan initial reserve system areas heavily impacted by human presence and activities, assuming they host species-poor communities, mostly composed of generalist species, expected to be less informative on bat responses to climate change. We also used information on travel time and road network layers to exclude planning units in remote areas hardly accessible and reachable. In fact, although such remote areas may be expected to host high habitat quality, and could therefore be informative in relation to climate change effects on bat communities, we preferred to rather prioritize relatively more pristine areas within Natura 2000 sites and PAs (see above) easily reachable by personnel, considering that monitoring activities could involve volunteers that might not have means to reach such areas. We incorporated information on human population, road network and travel time by computing values of human density, road density and average values of travel time, respectively, for each planning unit. Information on sources of layers used to set the cost function and define areas to lock out is provided in Table S2.

2.3. Marxan

2.3.1. Input data

2.3.1.1. Conservation features and climate change velocity. Marxan optimization included the proportion of planning unit area occupied by each of the 569 conservation features related to the predicted species range shifts (Fig. S1). For the 37 conservation features related to community turnover, we considered the weighted average of turnover values within planning units. Climate change velocity was scaled to an interval ranging from 0 to 1 relative to planning units and used as a relative multiplier, which can change the value that a planning unit has towards meeting the overall planning objective.

2.3.1.2. Cost function and initial reserve system-locking. We prioritized planning units with high coverage of Natura 2000 sites and PAs by

setting the cost function in the following way: 0–10% Natura 2000-PAs coverage (cost = 120), 10%–40% (60), 40%–70% (40), 70%–100% (20) (Fig. S1). We locked out from Marxan initial reserve system planning units with road densities within the last decile ($> 1.409 \text{ km/km}^2$) and human population densities above 1500 people/km², which is the low threshold of high-density clusters of the degree of urbanization classification (DEGURBA) of Eurostat (<https://ec.europa.eu/eurostat/web/degree-of-urbanisation/information-data>). Finally, we locked out planning units with road density equal to 0 and with travel time from urban centers above 120 min.

2.3.2. Run parameters

2.3.2.1. Europe. We performed three consecutive runs in which we progressively increased conservation feature targets from 1% to 3% and 5%, respectively. To facilitate gradual progression from one solution to the next while retaining essential information, we used Marxan's option of locking planning units in the initial reserve system. This involved incorporating the planning units selected in the optimal solution of the preceding run into the following, that is stations from the initial run (1%) being integrated into the second run (3%), and stations from the latter subsequently being included in the final run (5%). Notably, as conservation targets increase, there is a parallel increase in the number of selected planning units (i.e., monitoring stations) in the Marxan best solution (Ball et al., 2009). Consequently, the three resulting solutions represent incremental expansions of monitoring stations and effort, and the three conservation feature targets of 1%, 3% and 5% represent, therefore, monitoring targets. We set all runs with 1000 number of repeat runs, 10,000,000 number of iterations and Boundary Length Modifier equal to the default value.

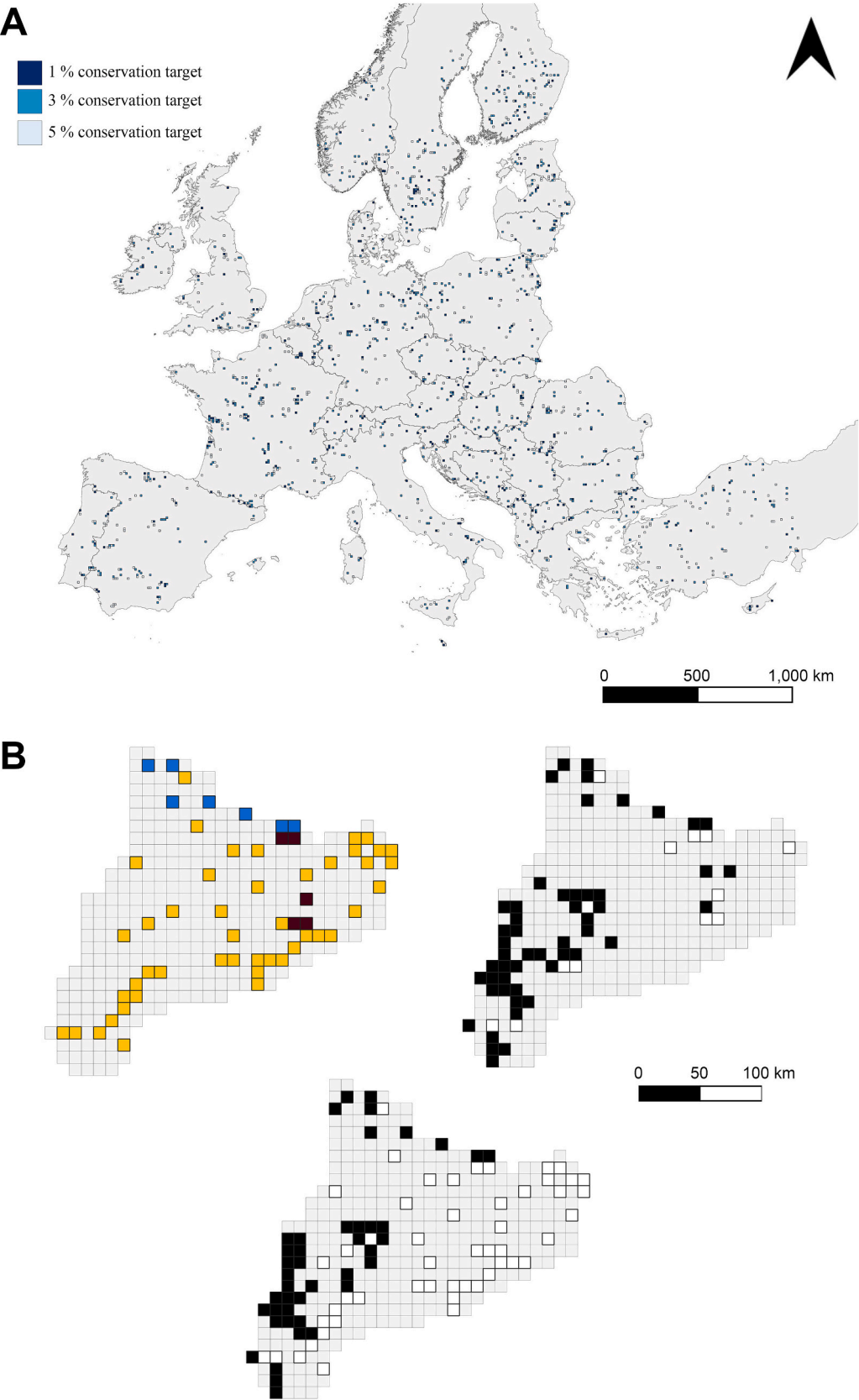
2.3.2.2. Catalonia case study. The ongoing 'Bat Monitoring Programme' (BMP; <https://www.batmonitoring.org/>) is a standardized monitoring initiative that systematically collects data on bat activity and species occurrence, and was not specifically designed to detect the effects of climate change on bat communities. Established in 2019 in Catalonia and subsequently extended across Spain, the BMP aims to expand to the rest of Europe (Torre et al., 2021; Santana et al., 2025). We used the BMP as a case study (only including data from Catalonia) to exemplify the integration and adaptation of an existing regional monitoring network for a climate-driven focus, aligned with the proposed European network.

Marxan settings and conservation features for this case study were modified from the European-level network runs (2.3.2.1 Europe) as follows. We excluded conservation features of species range shifts that were not occurring in Catalonia by setting feature targets to 0 and set to 1% the targets of the remaining 17 conservation features occurring in the region. We excluded the community turnover feature because, in preliminary analyses, it led to the inclusion of large clusters of planning units in the Marxan best solution due to the low geographic resolution of the layer, which is unsuitable for regional-scale analyses (Fialas et al., 2025). Finally, we locked out planning units outside Catalonia. We performed a first run in which planning units from the 5%-target European monitoring network (3.1 European network), and that were also inside Catalonia jurisdictional boundary, were locked in the Marxan initial reserve system. In a second run, we also locked in those planning units corresponding to the monitoring locations already included in the existing Catalanian monitoring program. Runs were executed with 1000,000 iterations.

3. Results

3.1. European network

We designed three European networks representing different targets in monitoring effort (1%, 3%, 5%; Fig. 2A). An increase in monitoring



(caption on next page)

Fig. 2. European and Catalanian monitoring networks designed to detect bat species range shifts under climate change. **A.** European networks derived from Marxan analyses under increasing conservation targets (1%, 3%, 5%). In sequential runs, planning units selected in the solution of the previous target were locked into subsequent runs, generating progressively larger networks and higher monitoring efforts. **B.** Catalanian networks. Top left: planning units covered by the existing Catalonia's Bat Monitoring Programme (BMP; orange); European network stations are shown in brown (overlapping with BMP) and blue (non-overlapping). Top right: first regional network with European network units locked in; selected units are shown in black (non-overlapping with BMP) and white (overlapping). Bottom: second regional network with both European and stations of the current Catalonia's BMP locked in; selected units are shown in black (non-overlapping with BMP) and white (overlapping). Unselected planning units are shown in light grey. See Table 1 for network statistics. Map lines delineate study areas and do not necessarily depict accepted national boundaries. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

effort targets was followed by a similar increase in the number of monitoring stations (i.e., planning units in Marxan) required to achieve such efforts, from 332 (1%) to 931 (3%) and 1589 (5%; Table 1). From the original 63,886 planning units, 19,646 were locked out from Marxan initial reserve system due to high levels of human population and road densities, absence of roads and high travel time from urban centers.

In all three monitoring target scenarios, every country with overlapping conservation features was allocated at least one monitoring station, with the sole exception being the Vatican City. For the largest network (5% of monitoring targets), the countries showing the highest number of monitoring stations were France (202 of 5279 total planning units) followed by Germany (120 of 3693 planning units) and Turkey (120 of 8251 planning units), while countries with the lowest number of stations were San Marino (1 of 4 planning units), Liechtenstein (2 of 2 planning units) and Andorra (2 of 4 planning units) (Fig. 2A). In all three networks, the vast majority of conservation features (94%) achieved the predefined representation targets, confirming that the selected planning units provided adequate spatial coverage under the specified monitoring targets (Table 1).

Site selection was also influenced by climate change velocity and community turnover, with monitoring stations often preferentially located in areas projected to experience more rapid climatic and community changes (Figs. S2–S3; see Supplementary Text for spatial

pattern descriptions). Guidelines for the practical implementation of the monitoring network are detailed in Supplementary Text.

3.1.1. Coverage of Natura 2000 and protected area networks

The cost layer facilitated the allocation process, resulting in the majority of monitoring stations being allocated to areas primarily concentrated within Natura 2000 sites and PAs. More precisely, 81%, 79.9%, and 79.4% of the stations within the networks with monitoring targets of 1%, 3%, and 5%, respectively, were found to intersect Natura 2000 sites, while 91.6%, 87.2%, and 84.9% intersected PAs in the same networks (Table 1). The coverage of Natura 2000 sites and PAs by monitoring networks increased with increasing levels of monitoring targets. Specifically, 2.7%, 6.1%, and 9.3% of Natura 2000 sites intersected with monitoring stations from the three networks of monitoring targets of 1%, 3%, and 5%, respectively. Similarly, 1.5%, 3.4%, and 5.4% of PAs intersected with stations from the same networks (Table 1).

3.2. Case study at a regional scale: Catalonia's network

Stations of the existing BMP cover 51 out of the total 391 Catalanian planning units (13%; Fig. 2B). Monitoring stations of the European network within Catalonia's jurisdictional boundary correspond to 12 planning units, most of them close to the border with France and Andorra (Fig. 2B).

The regional network obtained in the first run was composed of 65 monitoring stations, corresponding to 16.6% of the total Catalanian planning units and included the 12 monitoring stations of the European network within Catalonia (Fig. 2B; Table 1), which were locked in the Marxan initial reserve system (Fig. 2A). Among the 65 selected planning units, 13 matched stations of the current BMP (20% of the network; Table 1), while two thirds of the network fell outside the areas currently monitored in the region.

The network resulting from the second run included 94 monitoring stations, corresponding to 24% of the total Catalanian planning units (Fig. 2B; Table 1). This run also included both the 12 planning units belonging to the European network within the region (Fig. 2A) and planning units currently covered by the BMP, which were locked in the initial Marxan reserve system. Additional 43 planning units included in the Marxan solution were located outside the areas currently monitored in the region by the BMP (Table 1). All conservation features targets were met in the two runs (Table 1).

3.2.1. Coverage of Natura 2000 and protected area networks

Similar to the European network, most monitoring stations fell inside the Natura 2000 and PAs networks. Specifically, 93.8% and 95.7% of the stations of the first and second runs, respectively, intersected Natura 2000 sites and 93.8% and 94.7% of the stations of the same two networks intersected PAs (Table 1). The coverage of protected networks increased from the first to the second run due to the larger number of planning units, and hence the area covered by the second network. Specifically, 45.9% and 60.6% of Natura 2000 sites intersected stations of the first and second runs, respectively, while 35% and 49.7% of PAs intersected stations of the same two networks (Table 1).

4. Discussion

We propose a European-scale monitoring network specifically

Table 1

Statistics of the European (monitoring targets 1%, 3%, and 5%) and Catalanian monitoring networks. Network distributions are shown in Fig. 2. For the European network, totals of Natura 2000 sites (N2K) and Protected Areas (PAs; including Turkey) are 27,659 and 123,834, respectively, with 606 conservation features (569 related to species range shifts and 37 to community turnover). For Catalonia, planning units from the European network were locked in the first network scenario, while regional monitoring stations were additionally locked in the second network. Totals of Catalonia's N2K and PAs are 170 and 320, respectively, with 17 conservation features. A total of 53 planning units were excluded in both runs. Monitoring stations (MS) correspond to planning units selected in the Marxan best solution.

European Network			
Statistics	Monitoring Targets		
	1%	3%	5%
Number of MS	332	931	1589
MS intersecting N2K	269	744	1261
N2K intersected by MS	744	1681	2566
MS intersecting PAs	304	812	1349
PAs Intersected by MS	1841	4258	6733
Conservation features reaching target	94.06%	94.06%	94.06%

Catalan Network		
Statistics	Networks	
	1st	2nd
Number of MS	65	94
MS intersecting Catalonia's network	13	51
MS intersecting N2K	61	90
N2K intersected by MS	78	103
MS intersecting PAs	61	89
PAs Intersected by MS	112	159
Conservation features reaching target	100%	100%

designed to quantify the effects of climate change on European bats and provide guidelines and protocols for the practical implementation of monitoring activities. The network is designed to provide governance bodies and decision-makers with robust scientific evidence to inform proactive conservation actions and enable early measures to address climate-related risks to bat communities. The Catalonia case study demonstrates how an existing monitoring scheme, such as the BMP, can be scaled up and aligned with the objectives of the European network. This example illustrates how national or subnational initiatives can be complemented and adapted to detect climate-driven changes in bat communities.

4.1. Rationale for the design of the European-scale monitoring network

The proposed monitoring network and protocol align with general recommendations and good-practice principles that underpin effective biodiversity monitoring, including the clear formulation of a process-based monitoring hypothesis explicitly linking climate drivers to expected biodiversity responses, the definition of measurable indicators, the standardization of data collection procedures, and a sampling design whose statistical power to test the monitoring hypothesis could be evaluated once empirical monitoring data are collected (Dalton et al., 2023; Gonzalez et al., 2023; Legg and Nagy, 2006).

We considered the hypothesis that, if climate change affects European bats, it will cause species dispersal towards climatically suitable areas. Within the EBV framework (Jetz et al., 2019; Pereira et al., 2013), we used detectable changes in species distributions as proxies for bat community responses to climatic alterations, as alternative metrics, such as population densities and abundance, remain difficult to estimate reliably in bats (Kunz et al., 2009).

The methodological framework underlying the network design, based on the integration of SDMs and SCP tools and originally outlined by Amorim et al. (2014) and Carvalho et al. (2016), was adapted to meet our specific monitoring objectives and practical implementation needs by defining the conservation features and cost function of the Marxan objective function to optimize the selection of geographic areas where species distributional changes are expected to be rapid, detectable, logistically monitorable, and representative of climate change impacts on bat communities. Importantly, the proposed network is designed to detect signals consistent with climate-driven changes in species distributions, rather than to formally disentangle causality between climate change and observed distributional changes. In addition, while SDMs provide a robust and widely used framework to project potential distributional shifts under future climatic scenarios, we acknowledge that such projections are inherently associated with uncertainties. These uncertainties may influence the exact spatial configuration and magnitude of predicted changes, but do not undermine the general expectation of climate-driven redistribution patterns underlying the monitoring hypothesis. Accordingly, SDM-derived layers were interpreted as spatially explicit hypotheses to guide monitoring design, rather than as exact predictions of future bat distributions.

Given the broad geographic extent of the monitoring region, Marxan produced a spatially optimized network design that allocated monitoring efforts efficiently across space. Following network implementation, we suggest to ensure temporal replication, through repeated sampling of the same sites over multiple years, which would facilitate the detection of long-term climate-driven trends against distributional shifts due to short-term weather fluctuations or other site level disturbances. We also suggest that, following network implementation, power analyses should be performed. Such analyses would quantify the sensitivity of the network to detect spatially and ecologically meaningful changes and provide an explicit measure of confidence in its ability to support or refute the monitoring hypothesis. Periodic assessments of network efficiency could then be used to refine and optimize the network design based on accumulated monitoring data, in accordance with the principles of adaptive monitoring sensu Lindenmayer and

Likens (2009).

Regarding practical network implementation aspects, the splitting of the projected SDM and community turnover layers at the country level ensured a minimum number of monitoring sites in each European country (with the exception of the Vatican City), a relevant political consideration for implementation within the EU, as it allows reporting obligations by all member states. Finally, we provided three network configurations corresponding to distinct monitoring target thresholds, representing increasing numbers of monitoring sites and associated effort levels, thereby offering decision-makers multiple implementation options depending on the availability of human and financial resources. These target levels (1%, 3%, and 5%) are intended as operational scenarios, rather than as optimal or recommended thresholds, and the network deriving from 1% of monitoring target should be considered as the minimum operational monitoring scenario, that is the smallest network expected to ensure representation of the conservation features while remaining feasible under limited workforce and funding availability. More generally, the proposed networks should be interpreted as operationally informed spatial prioritization scenarios rather than as the only possible optimal configurations. Accordingly, it should be considered that alternative spatial configurations could achieve comparable levels of network efficiency and target representation, since the precise identity of selected planning units may be sensitive to operational settings, while alternative units can contribute similarly to the monitoring objectives, especially in extremely large initial reserve systems (i.e., 63,886 planning units) such as the continental-scale system considered here. In this context, Marxan was used to select planning units from a candidate set defined according to ecological representativeness, logistical feasibility and practical implementation constraints. These criteria are necessarily partly expert-informed, but they are transparent, reproducible and can be adapted in future applications if monitoring needs, available resources or implementation constraints change.

4.2. Integrating existing national and subnational monitoring networks: The Catalan case study

Data used to assess biodiversity responses to environmental changes often vary in spatial and temporal coverage and in taxonomic scope, limiting the ability to draw consistent conclusions that can effectively inform decision-making and conservation planning (Gonzalez et al., 2016; Mihoub et al., 2017; Navarro et al., 2017; Pereira et al., 2012). Such inconsistencies often arise because monitoring activities are organized within political boundaries, whereas biodiversity and the drivers of its change rarely align with administrative borders (Kühl et al., 2020; Navarro et al., 2017).

This is evident in Europe, where despite the existence of numerous biodiversity monitoring programs, substantial monitoring gaps persist, largely due to the absence of coordinated transnational initiatives (Moersberger et al., 2024; Santana et al., 2025). Where national or subnational programs are in place, they often differ in sampling protocols and design, preventing their effective integration at the continental scale (Moe et al., 2023; Moersberger et al., 2024; Santana et al., 2025). However, these ongoing programs constitute invaluable monitoring resources, supported by well-established field networks and trained workforces, which should not be overlooked and could play a key role in meeting both national and continental biodiversity policy targets if integrated within a unified framework (Santana et al., 2025). Our proposed European network, together with the practical guidelines provided for implementing and standardizing monitoring activities, was conceived as a unified framework to help close such transnational monitoring gaps by building upon and complementing, rather than replacing, existing national and regional programs. This dual approach aims (1) to engage local expertise and infrastructure in implementing monitoring activities at the sites selected for European-level assessments, and (2) to potentially complement and adapt ongoing regional programs so that they can provide information on climate change effects

on local bat communities, therefore informing national and subnational conservation decisions.

The Catalonia case study demonstrates that our climate-driven monitoring design produced a different configuration of monitoring sites compared with the existing BMP, even when all BMP stations were forced into the Marxan output network. This outcome indicates that the current BMP design may not be optimally suited to detect climate change effects on bat distributions. By incorporating 52 additional monitoring stations identified by the optimization algorithm as priority areas outside the current BMP network in the first Marxan run, where BMP stations were not locked into the best solution, the program could be adapted to become informative on climate-driven changes in Catalan bat communities. Therefore, adapting existing non-climate-focused monitoring programs can provide an efficient strategy to fill biodiversity monitoring gaps across Europe, accelerating the establishment of a European-scale network while maximizing the value of ongoing national and regional monitoring efforts (Santana et al., 2025).

4.3. Monitoring network and its design approach as support tools for European Union's biodiversity policy framework

Over recent decades, the critical importance of halting biodiversity loss has been widely acknowledged at the international level, leading to the adoption of global frameworks and legally binding agreements aimed at conserving biodiversity (CBD, 2022; 1992). Within this global effort, the EU and its Member States have been at the forefront in progressively defining and reinforcing ambitious commitments to biodiversity conservation at both the European and global scales (Hermoso et al., 2022; Moersberger et al., 2024; Viti et al., 2024). Building on the cornerstone Habitat Directive, the EU's most recent and comprehensive policy instruments for biodiversity conservation are the Biodiversity Strategy for 2030 (COM/2020/380 final; EC, 2020) and the newly adopted Nature Restoration Regulation (Regulation (EU) 2024/1991; EC, 2024). Together, these policy instruments place strong emphasis on restoring biodiversity and ecosystems to enhance their resilience to climate change and to contribute directly to the EU's mitigation and adaptation objectives.

Our proposed European-scale monitoring network, together with the climate-driven monitoring design applied at the regional level, can assist the EU and its member states by providing information relevant to national, communitarian, and international commitments under the current biodiversity policy framework by generating informative data on biodiversity response to climate change. Our monitoring proposal can also support broader conservation and reporting objectives of the EU and its member states. A standardized, long-term monitoring program could provide information relevant to member states in meeting the Habitat Directive reporting obligations under, for example, Article 17, which requires information on the distributional range, population trends, habitat conditions, and prospects of species of community interest (EC, 1992). This applies not only because the network was designed for bats, a taxonomic group entirely listed under Annexes IV of the Directive and with 14 species listed in Annex II, but also because the monitoring network was optimized in a way that allocates significant efforts to Natura 2000 sites. In addition, the 10×10 km grid used to define planning units corresponds to the reference grid adopted for the Habitat Directive periodic reporting (<https://www.eea.europa.eu/>). The new Nature Restoration Regulation will maintain a focus on priority habitats and species of community interest listed under the Habitat Directive and reinforce the current periodic reporting obligations through strengthened requirements for more frequent monitoring of restoration progress of ecosystem, habitat, and species (EC, 2024).

Complementing these reporting obligations, the Biodiversity Strategy for 2030 calls for (1) a more climate-resilient PA network through the designation of new PAs and the enhancement of ecological connectivity to facilitate species movements, and (2) the effective management of all PAs to ensure long-term conservation of biodiversity. In

this context, the proposed climate-informed monitoring network and design, with most sites overlapping EU's PAs, could contribute to supporting these policy targets. To meet them, decision-makers require information to both anticipate climate-driven species redistributions and set suitable conservation strategies based on site-specific, long-term data capturing biodiversity features of each area and the ecological requirements of the species they support. Such information can only be generated through scientifically robust, hypothesis-driven, and sustained monitoring programs (EC, 2020; Dalton et al., 2023; Gonzalez et al., 2023).

Taken together, our findings highlight the potential of a climate-informed, hypothesis-driven monitoring framework to support biodiversity conservation under ongoing environmental change. By integrating SDMs with SCP, the proposed approach provides a scalable and policy-relevant tool to anticipate and detect climate-driven changes in species distributions. The flexibility of the framework, together with its compatibility with existing monitoring programs, supports its implementation through coordinated European initiatives and its integration into current biodiversity monitoring infrastructures. Although developed for bats, the approach is broadly transferable across geographic regions and taxonomic groups, provided sufficient distributional data are available. More broadly, this study underscores the importance of coordinated, long-term monitoring efforts to generate robust evidence on biodiversity responses to climate change. Such efforts will be essential to support conservation strategies and to meet the increasing demands of European and international biodiversity policy frameworks.

CRediT authorship contribution statement

Francesco Belluardo: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Formal analysis. **Federica Roscioni:** Writing – review & editing, Writing – original draft, Validation, Formal analysis. **Adrià López-Baucells:** Writing – review & editing, Writing – original draft, Validation, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Daniilo Russo:** Writing – review & editing, Validation, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Luca Santini:** Writing – review & editing, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Penelope C. Fialas:** Writing – review & editing, Investigation. **Hugo Rebelo:** Writing – review & editing, Validation, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Orly Razgour:** Writing – review & editing, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Francisco Amorim:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.biocon.2026.112113>.

Data availability

All data and code used in this study are publicly available on Mendeley Data (<https://doi.org/10.17632/tc374p574s.2>).

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